

Comparison of the RF Fields Distribution Between a High-Permittivity Material and a Metasurface for Magnetic Resonance Imaging

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Abstract— Different novel solutions have been explored to improve the fields distribution for Magnetic Resonance Imaging. High Permittivity Materials and metasurfaces have shown very promising results for enhancing the Signal to Noise Ratio and the Transmit Efficiency. In this work, through numerical simulations, we analyze the electromagnetic field distribution in a cubic phantom when two dipoles are used to generate the radiofrequency fields for three cases: when no additional devices are used to manipulate the fields, and when a metasurface and a High-Permittivity Material are positioned between the coil and the phantom. The results show that the metasurface and High-Permittivity Material significantly contribute to enhance the fields in the phantom. Specifically, the metasurface improve the fields in locations closer to the coil, while the High-Permittivity Material perform better in locations far from the coil.

Keywords—MRI; High-Permittivity Materials; metasurface; numerical simulations; propagation

I. INTRODUCTION

In Magnetic Resonance Imaging (MRI), the radiofrequency (RF) field B_1 is used to detect the signal from the patient's tissues. Nowadays it is becoming popular the use of solutions such as metasurfaces and High-Permittivity Materials (HPM) to obtain a desired profile of the B_1 field.

Metasurfaces are artificial structures having unusual electromagnetic properties, as negative permittivity or permeability. The role of these structures, when properly designed, consists in the improvement of the magnetic field homogenization within the ROI, strictly correlated to the signal-to-noise ratio.

HPM, on the other hand, exploit high local displacement currents which can act as an additional source of fields not fully confined in a conducting coil but more distributed in the whole HPM geometry. In addition, when the HPM surrounds the target

object, it can also act as a waveguide, making it possible to excite voxels that are positioned far from the coil.

HPM have been already used extensively in MRI. Both in simulations and experiments, they have shown a significant ability to improve local Signal to Noise Ratio (SNR) [1]-[3], Transmit Efficiency (TxEff) [1]-[2], signal homogeneity[4]-[5] and reduce Specific Absorption Rate (SAR)[6]. For example, an HPM helmet could provide an SNR increase of about 21% in the cerebrum, and 56% TxEff increase at the center of the brain [1].

Similarly, SNR and TxEff were increased near a metasurface when it was inserted between a 16 channels birdcage volume coil operating at 128 MHz, corresponding to the Larmor frequency of a 3T MRI scanner, and a phantom [7]. In this work, through numerical simulations, we are going to evaluate the ability to improve the electromagnetic field distribution in a phantom when a metasurface and an HPM pad are used.

II. METHODS

The electromagnetic fields were computed with the commercially available electromagnetic solver based on the Method of Moments (Feko Suite, Altair, Troy, MI, USA). Two dipoles were used to transmit the fields in a phantom having permittivity $\epsilon_r = 80$ and conductivity $\sigma = 0.5$. To realize a realistic scenario, the phantom dielectric properties are calculated at the operative frequency. We have compared the fields distribution for three different cases when, in addition to the dipoles and the phantom, a) no HPM and no metasurface were present; b) only HPM was present; and c) only metasurface was present. (Fig. 1). The phantom has the shape of a parallelepiped having size $100 \times 100 \times 200$ mm and it is placed 13 mm far from the source (the dipoles).

The metasurface and the HPM pad are placed between the dipoles and the phantom. In the first case, the metasurface is 5 mm far from the source. The metasurface is completely passive and it is excited thanks to the mutual coupling between

each cells and the dipoles. The HPM pad is placed at the same distance from the source, and it has the same length and width of the phantom, and a 5 mm thickness. The HPM material has permittivity $\epsilon_r = 110$ and conductivity $\sigma = 0.016$.

The magnetic metasurface has been designed to take into account the operative frequency, covering a 15 cm $\times$ 15 cm area [8]-[9]. More in detail, the metasurface unit-cell consisted of 2 – turns coil, made resonant with the use of properly designed capacitor. Specifically, the unit cells radius is equal to 5 mm and they are placed 2 mm apart from each other.

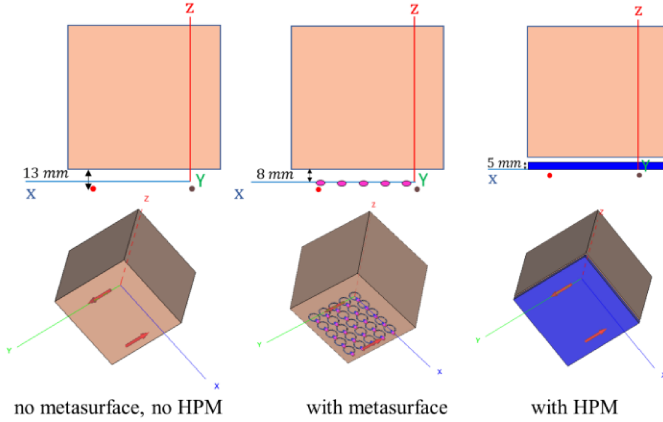


Figure 1 Schematic and 3D view of the numerical set-up. Three cases were simulated: a dipole and a cubic phantom., with: (a) no HPM and no metasurface (left); (b) only metasurface (center); (c) only HPM (right).

III. RESULTS AND DISCUSSION

With the aim of evaluating the behavior of the 3 systems at different distance from the two dipoles, we analyzed the magnetic field distribution respectively at 3 cm and 20 cm (Fig. 2).

It can be observed that the worst performance is obtained in the first case, when no HPM helmet and no metasurface are used (Fig. 2). For a given distance between the source and the corresponding xy plane, the metasurface can significantly enhance the field in voxels near the coil (Fig. 2a), with an improvement of at least 3 fold with respect to the other cases.

On the contrary, HPM pad is able to excite voxels of the phantom located far from the coil (Fig. 2b), with at least 2 fold improvement with respect to the other cases. Indeed, in this case, the selected xy plane is 20 cm far from the sources.

IV. CONCLUSION

In conclusion, both HPM and metasurfaces can enhance the fields distribution in a phantom, but in different locations. These findings suggest that an even better solution would involve the combined use of HPM and metamaterials, for a more homogeneous overall enhancement of the fields in the phantom.

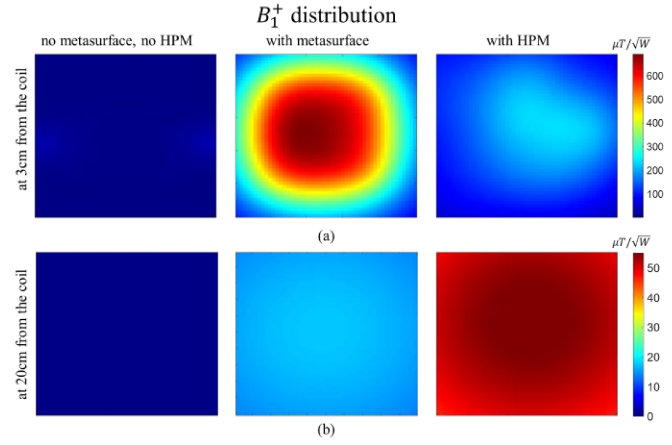


Figure 2. For all the three considered geometries, no metasurface and no HPM(left), with metasurface (center), with HPM (right), plot of the B_1 field distribution at 3 cm from the source (top), and at 20 cm from the source (bottom)

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REFERENCES

- [1] K. Lakshmanan, et al. "Improved whole - brain SNR with an integrated high - permittivity material in a head array at 7T." *Magnetic Resonance in Medicine*, 86, vol. 2, 2021, pp. 1167-1174.
- [2] G. Carluccio, C. M. Collins, "High-permittivity pads to enhance SNR and transmit efficiency in MRI of the heart at 7T: a simulation study." *Magn. Res. Mat. in Phys., Bio. and Med.*, 31, pp. 1-7, 2022.
- [3] G. Carluccio, G. Haemer, C. M. Collins, "SNR improvement when a High Permittivity Material helmet-shaped former is used with a close-fitting Head Array." In *2018 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 2018, pp. 304-306.
- [4] W. M. Teeuwisse, W. M. Brink, A. G. Webb, "Quantitative assessment of the effects of high - permittivity pads in 7 Tesla MRI of the brain." *Magnetic resonance in medicine*, 67, vol. 5, pp. 1285-93, May 2012.
- [5] W. M. Brink WM et al. "High permittivity dielectric pads improve high spatial resolution magnetic resonance imaging of the inner ear at 7 T." *Investigative radiology*, 49, vol. 5, pp. 271-7, May 2014.
- [6] N. P. Gandji, et al. "Displacement current distribution on a high dielectric constant helmet and its effect on RF field at 10.5 T (447 MHz)." *Magnetic resonance in medicine*, 86, vol. 6, pp. 3292-303, December 2021.
- [7] S. Rotundo et al. "A Passive and Conformal Magnetic Metasurface for 3T MRI Birdcage Coil" In *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 2023.
- [8] D. Brizi and A. Monorchio, "An Analytical Approach for the Arbitrary Control of Magnetic Metasurfaces Frequency Response," in *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 6, pp. 1003-1007, June 2021, doi: 10.1109/LAWP.2021.3069571.
- [9] Brizi, D., Monorchio, A. Magnetic metasurfaces properties in the near field regions. *Sci Rep* 12, 3258 (2022). <https://doi.org/10.1038/s41598-022-07378-y>.